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STRESSES UNDER MOVING VEHICLES

A PILOT STUDY OF WES EARTH PRESSURE CELL ACTION IN COMPARATIVELY SOFT SOIL

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PREFACE

This paper presents results of a pilot study on stress distribution conducted in connection with the vehicle mobility research program authorized by the Office, Chief of Engineers, for fiscal year 1956.

Personnel of the Waterways Experiment Station actively engaged in the study were Messrs. W. J. Turnbull, C. R. Foster, A. A. Maxwell, S. J. Knight, R. G. Ahlvin, A. B. Thompson, and M. D. Beasley. This paper was written by Mr. Thompson.

CONTENTS

SUMMARY

A pilot study was conducted to determine whether static and dynamic stresses induced in fairly soft soils by a pneumatic tire could be measured satisfactorily with the WES earth pressure cell. The study showed that the measurements were of the same order of consistency and accuracy as measurements made with the WES cell under static loads in firmer soils. Experience in placement of pressure cells and other test techniques was gained which will be valuable in future tests of this general nature. Preliminary observations were made of the effect of tire pressure, speed of truck, and repetitive passes on stresses induced at various depths. A limited study was performed to compare measured stresses with stresses computed according to Boussinesq's equations.

STRESSES UNDER MOVING VEHICLES

A PILOT STUDY OF WES EARTH PRESSURE CELL ACTION IN COMPARATIVELY SOFT SOIL

PART I: INTRODUCTION

1. This paper describes a pilot study made to determine whether static and dynamic stresses set up in fairly soft soils by pneumatic tires can be measured satisfactorily with the WES earth pressure cell and incidentally to develop techniques of testing and data collection.

2. The study consisted of (a) construction of a test lane of fat clay (locally termed buckshot clay) in which WES earth pressure cells were placed at various depths and offsets; (b) application of traffic with a self-propelled 2-1/2-ton truck loaded to 17,400 lb gross weight, and having tire pressures of 15, 50, and 60 psi; and (c) measurement of stresses under static and dynamic loads, and determinations of soil conditions before and during the tests.

PART II: TEST AREA AND EQUIPMENT

Test Area

Layout

3. The test area, constructed under a shelter on the Waterways Experiment Station reservation in a north-south direction, was 10 ft wide by 30 ft long and was divided into three 10-ft-square sections. Two parallel lines, one 4 ft from the east edge of the area and the other 3 ft from the west edge, were staked out as "center lines" for the pressure cell installations. Plate 1 shows the layout of the test area (section 3 contained no pressure cells).

Method of construction

4. The test area was first excavated to 3 ft below the natural ground elevation and then backfilled with selected soil in 6-in. lifts. Each lift was brought to the proper water content, mixed, and compacted with a 50-ton pneumatic-tired roller to achieve a uniform CBR of about 5 per cent throughout the 3-ft depth.

Soil

5. The soil used was a fat clay classified as CH under the Unified Soil Classification System. Classification data for this material are shown on plate 2.

Pressure Cells

Description

6. The pressure cells used were the WES earth pressure, four-gage type. These cells are 6 in. in diameter and are fabricated from stainless steel. They contain a mercury-filled fluid chamber with diaphragm, and a full Wheatstone bridge circuit made up of four SR-4 electrical resistance strain gages hermetically sealed within the cell. Details of the cell are shown on fig. 1 and plates 3 and 4. Pressure applied on the

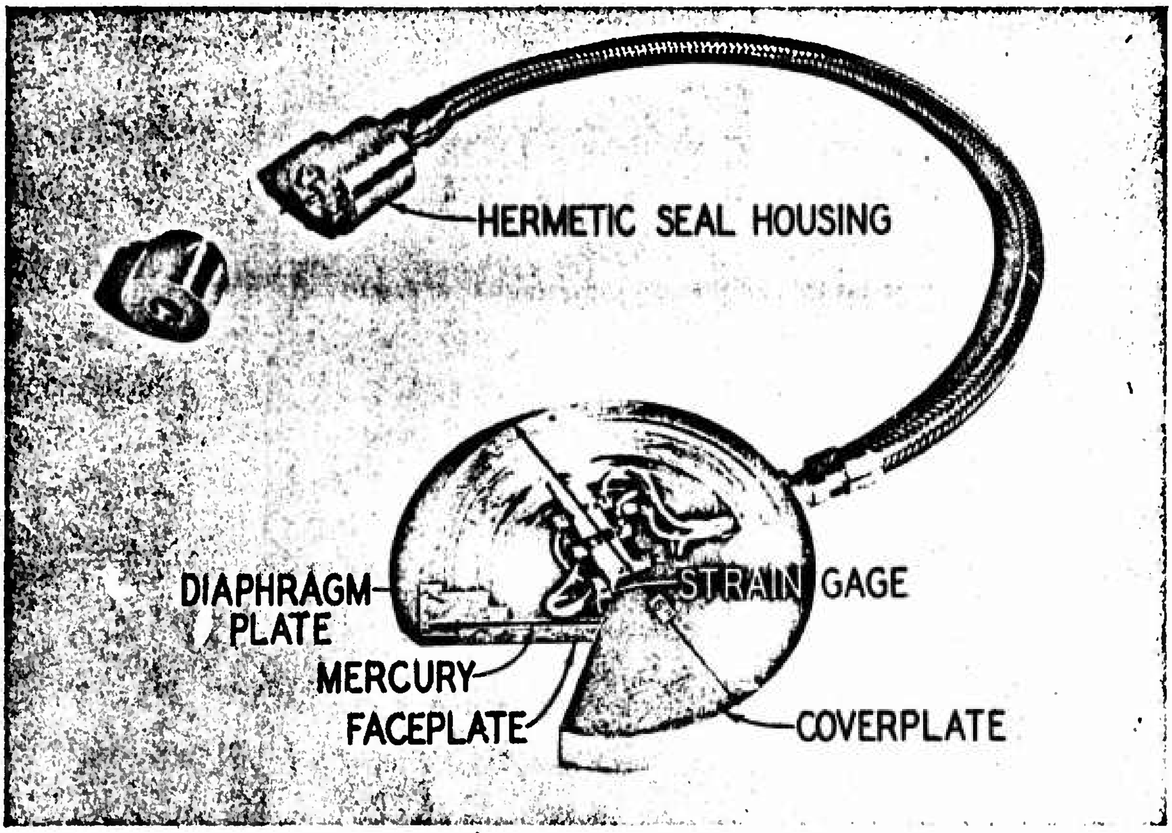

Fig. 1. Waterways Experiment Station earth pressure cell

face plate of the cell is transmitted through the mercury in the fluid chamber onto an internal flexible diaphragm and produces deflection of the diaphragm proportional to the load. The four SR-4 strain gages are mounted on the diaphragm and are actuated as the diaphragm bends. The use of the full Wheatstone bridge circuit practically eliminates the effects of temperature and of resistance variations in the lead-in wires. The strain gage readings are calibrated against the load on the face plate of the cell. A 60-microinch movement of the SR-4 strain gage corresponds to a 1-psi load on the face plate of the cell. The strain is measured by an electrical strain indicator connected to the cell. For these tests, readings on the cells were made through the strain indicator and recorded directly in pounds per square inch on a Brush multichannel recorder (see fig. 2). The cells used are rated at 50-psi maximum capacity, but have a safety factor of nearly 2.

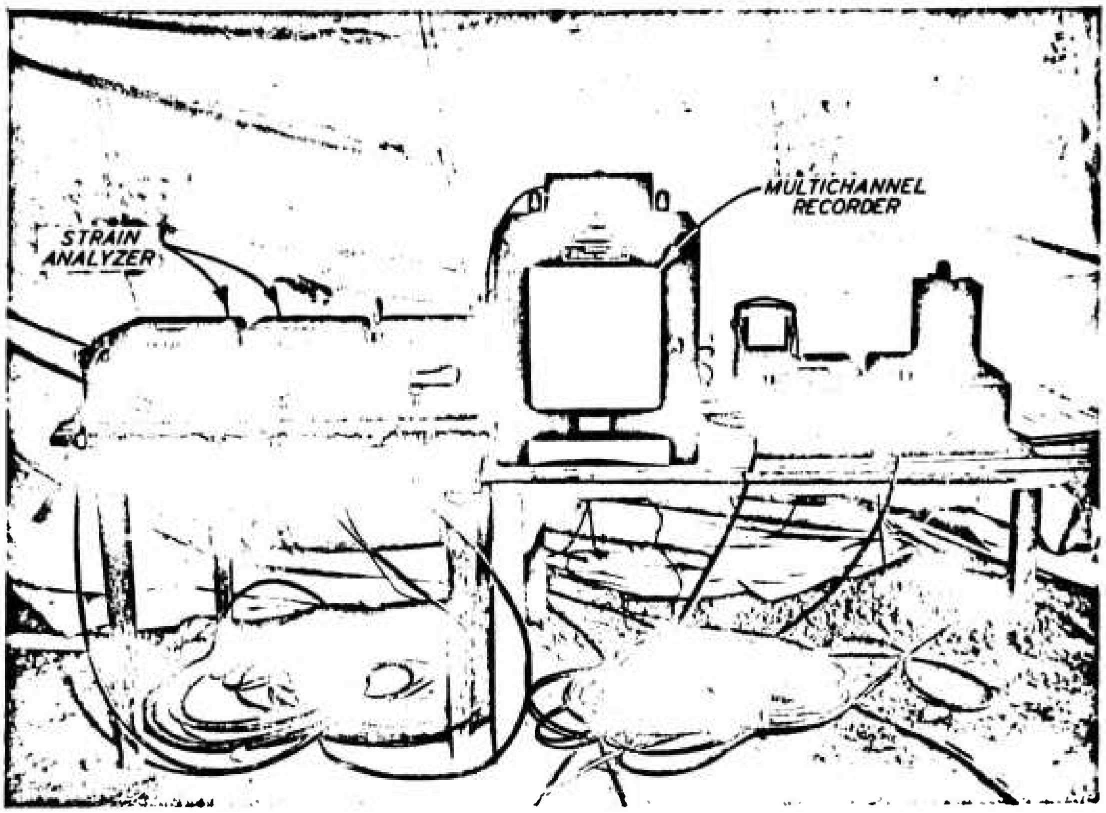

Fig. 2. Recording instruments used in the study

Calibration

7. Each cell was carefully calibrated prior to installation by application of a series of accurately measured loads in a specially designed chamber. The chamber was arranged so that air pressure acted against each of two thin rubber diaphragms between which the pressure cell was placed. The calibration curves were used to convert readings from microinches per inch strain of the SR-4 strain gages on the pressure cell diaphragm to pounds per square inch pressure on the cell.

Installation

8. After the test section was constructed, two series of cells were installed in the subgrade: one in section 2 at a depth of 6 in., and the other in section 1 at 3- and 9-in. depths. Also, one cell (No. 94) was installed at the ground surface in the unused portion of section 1 to measure surface pressures produced by the wheels of the test vehicle. The installation procedure consisted of locating the station at which the cells

were to be installed; digging a hole approximately 7 in. in diameter (1 in. greater than the cell) to the required depth; placing the cell in a horizontal position at the required depth, then replacing the soil, and compacting it to the strength of the surrounding soil. Fig. 3 shows the cells in the holes prior to replacement of the soil.

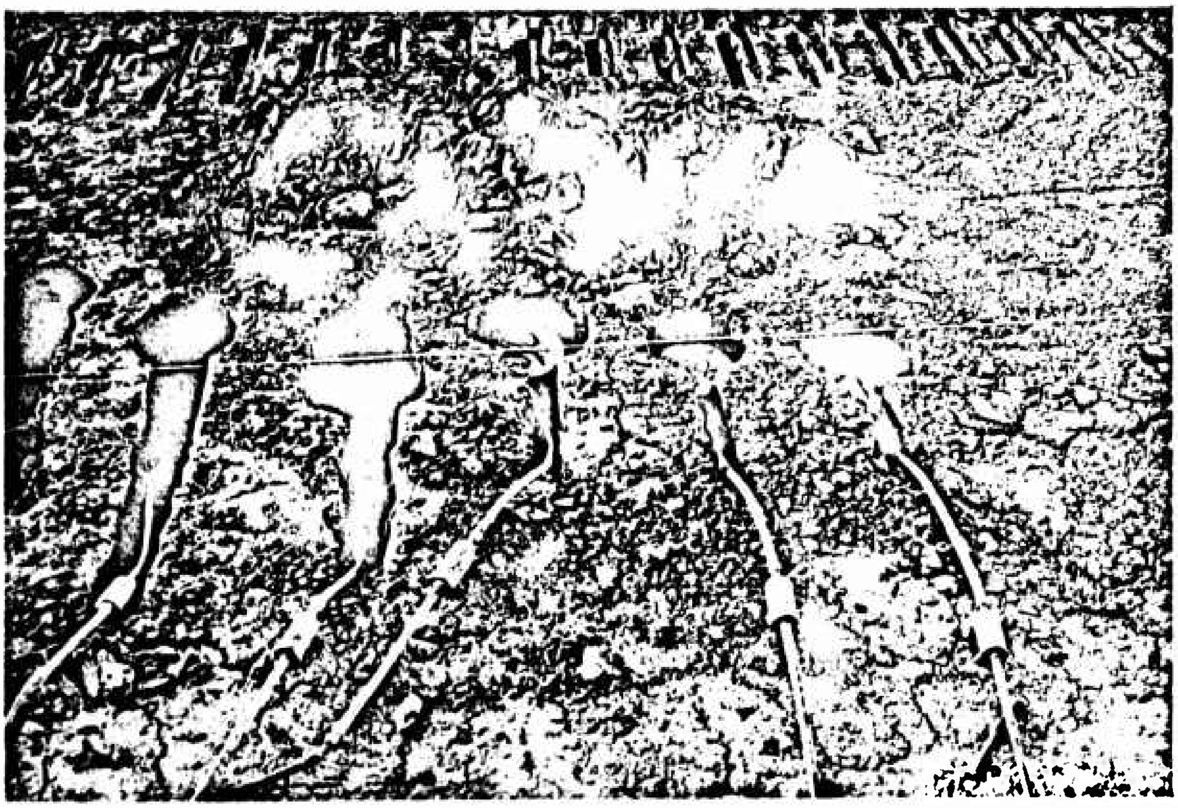

Fig. 3. Cells in place prior to replacement of soil

Location

9. The series or line of cells located at the 6-in. depth in section 2 was installed as shown on plate 1; three cells were placed approximately 3 ft apart in a line (called center line hereafter) and two cells were placed at 6- and 12-in. offsets, respectively, from the center line. The offset cells were placed on 1-ft centers from cell 2 to determine if close installation affects cell readings. These cells were designated as the first series.

10. The center line for the second series was 3 ft from the west or left edge of section 1 (see plate 1). The 3-in.-depth cells were installed

first; cell 1 was located on the center line and cells 2 and 3 were located at 3- and 6-in. offsets, respectively, from the center line and 1 ft apart measured along the line. The first 9-in.-deep cell (No. 4) was placed on the center line; cells 5 and 6 were installed at 9-in. depths at 6- and 12-in. offsets, respectively, and 1 ft apart measured along the center line.

Test Vehicle

11. The test vehicle was a 2-1/2-ton, 6x6 truck (M135) equipped with single tandem wheels and 11.00x20, 12-ply rating tires. Normally, the rear wheels of the M135 are inset 2-1/2 in. from the front wheels. Since it was desired that all the wheels on one side of the truck track each other, 2-1/2-in. spacer blocks were placed on all rear wheels. The arrangement of the wheels of the truck and the approximate load per wheel are shown on fig. 4. The truck was loaded with a 5000-lb load distributed

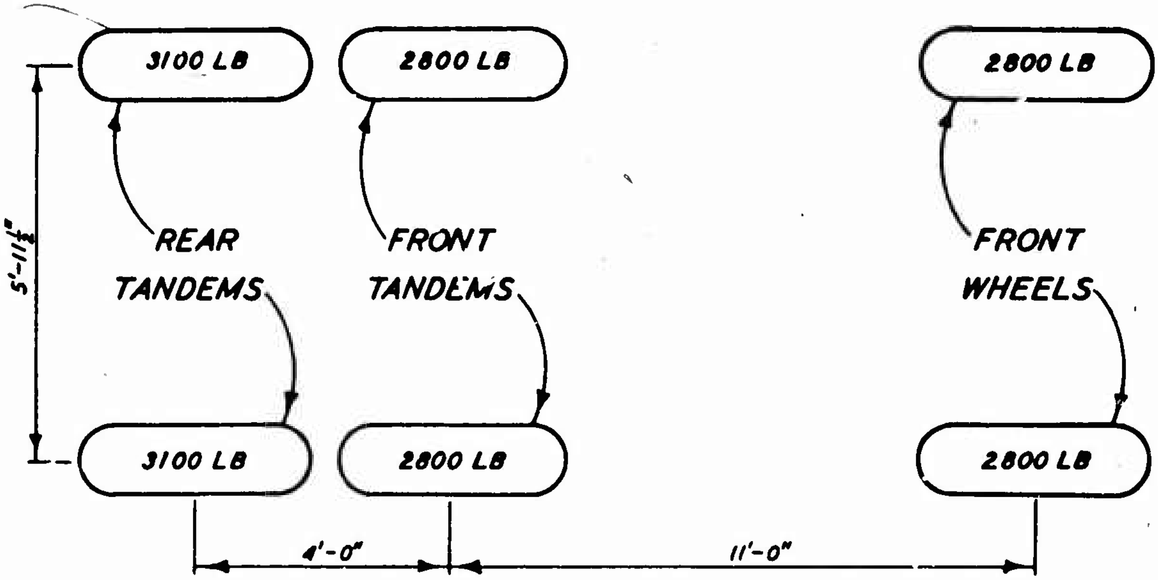

Fig. 4. Arrangement of wheels of test vehicle and load per wheel

as equally as possible over the bed of the truck. After loading, each set of wheels was weighed and the total load (17,400 lb) determined. The weight on the front wheels and front tandem wheels was approximately

5600 lb per set or an average of 2800 lb per wheel, whereas that on the rear tandem wheels was 6200 lb or an average of 3100 lb per wheel. Tests were run at 15-, 50-, and 60-psi inflation pressures, which correspond to average contact pressures on a firm surface of 30, 50, and 53 psi, respectively, obtained by dividing the total vehicle weight (17,400 lb) by the total gross area of the tires in contact with the surface at the respective inflation pressures. Average contact pressures for 15- and 50-psi tire pressures were also computed using only the total area of tread rubber in contact with a firm surface. These were 58 and 84 psi, respectively.

12. Sketches of the tire prints at 15-, 50-, and 60-psi inflation pressures, gross load 17,400 lb, on a hard surface, are shown on fig. 5.

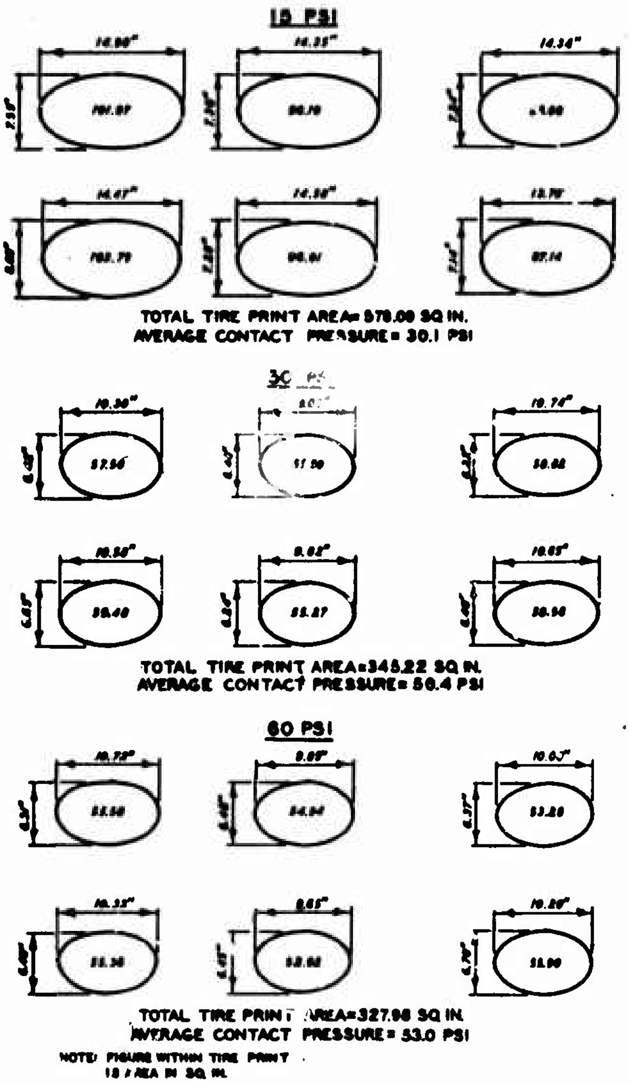

Fig. 5. Dimensions of tire prints and contact pressures of tires at inflation pressures of 15, 50, and 60 psi

PART III: TEST PROCEDURES

Traffic Application

13. Traffic was applied over the cells with the truck in forward motion and all wheels driving in low gear, low range. Only one line of wheels was used to apply the load; the other line of wheels was run in a guide channel (see fig. 6), constructed to the same width as the tire,

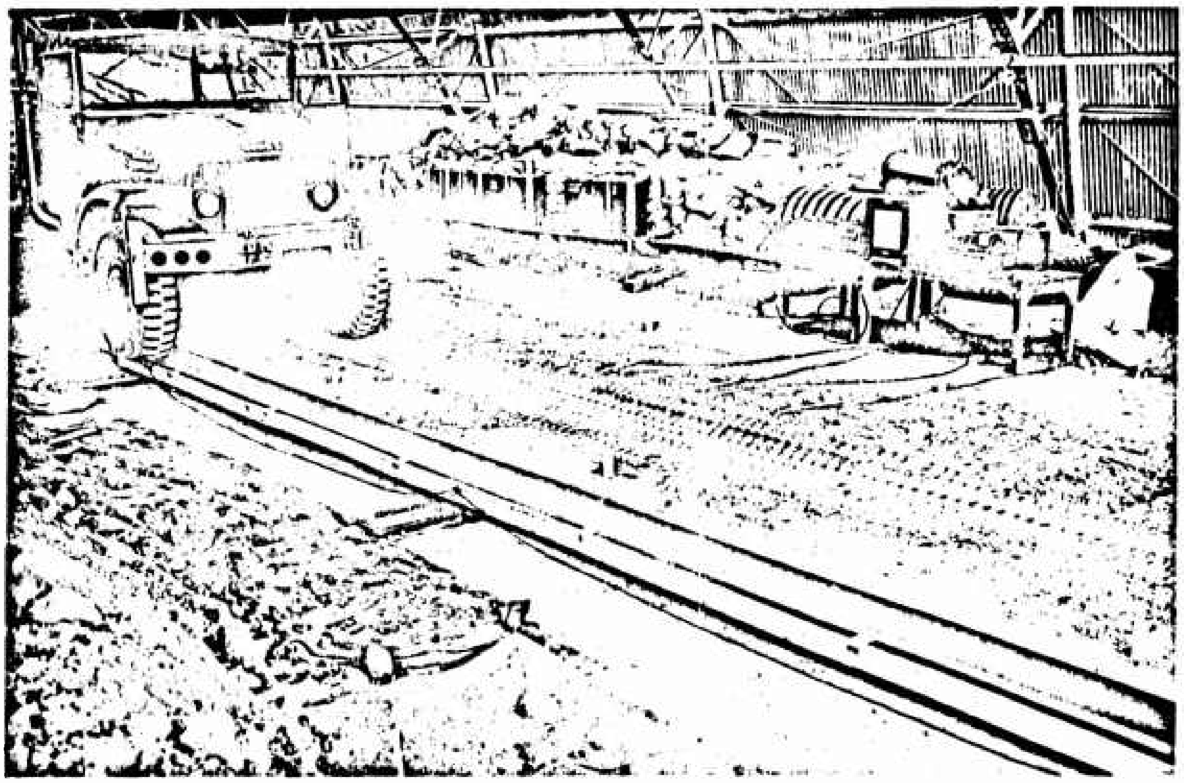

Fig. 6. Guide channel with truck in position to begin a pass

so that alignment of the wheels over the cells could be maintained. The channel was so constructed that it could be moved to any required offset from the center line of cells. The first pass or application of load was usually made over the center line of cells; then the channel was offset and the next pass was made. With this method, load was applied directly over some cells and at offsets of 3, 6, 9, and 12 in. from other cells, depending upon the cell location.

14. Microswitches were mounted on a rail along the guide channel and a marking device to actuate these switches was mounted on the front

bumper of the test vehicle in order that the truck speed and position could be determined at any time during a pass. As the truck moved forward the device was moved along the rail and when it came in contact with the switch a mark was automatically made on the recording chart. Microswitches were so placed that a mark was made at the instant the center of the front wheel (and later, the rear tandem) was over the center of a cell. See plate 5. Fig. 7 is a close-up of the channel, microswitch, and marker device. With the position of the microswitches, the location of the marker with respect to the truck wheels, the location of the cells, and the speed of the paper on the recording chart known, the truck speed and location at any time could be determined.

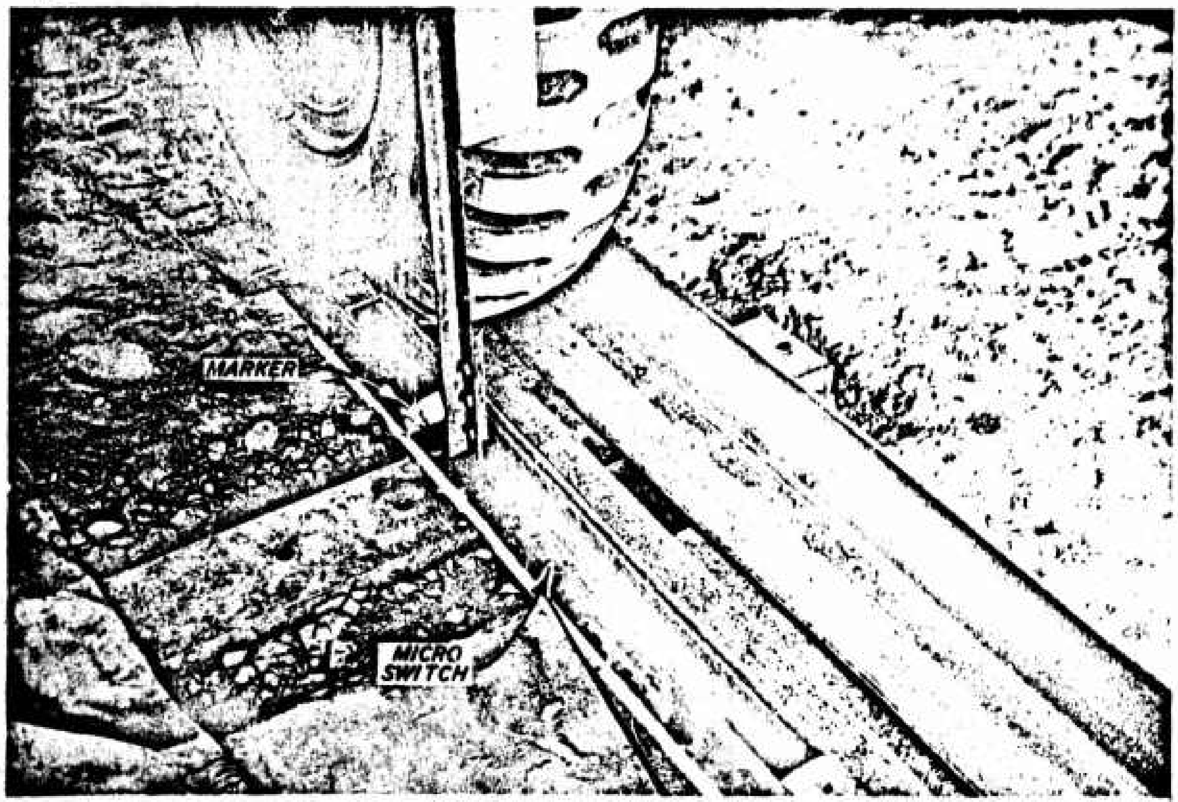

Fig. 7. Close-up of guide channel, microswitch, and marker

Dynamic and Static Load Tests

First cell series

15. Dynamic loads under a 15-psi tire pressure were first determined on the cells at the 6-in. depth. At vehicle speeds ranging from

1 to 4 mph (maintenance of a constant rate at low speeds was difficult), a pass was applied along the center line and at offsets of 18, 6, 24, and 12 in. in the order mentioned. The next eight passes were along the center line and were followed by a repetition of the pattern of the first five passes. Thus, ten passes were made directly over the cells on the center line, two over each of the 6- and 12-in. offset cells, and four passes were not directly over any of the cells.

16. Dynamic loads under a 60-psi tire pressure were then determined for the first series of cells. One pass was applied along the center line and at offsets of 12 and 6 in. in the order mentioned; then eight passes were applied along the center line, followed by three passes at 12- and 6-in. offsets, respectively.

17. Upon completion of the dynamic testing, the static load under the front wheel only at 15-psi tire pressure was measured directly over cell 5 (6-in. depth), because this cell (and cell 4) had received the least amount of traffic. Three measurements of the load were made.

18. One static load and three dynamic loads at 15 psi were applied to the cell at the 0-in. depth (cell 94) in section 1 (see paragraph 8), followed by one static load and six dynamic loads at 50 psi. A 50-psi tire pressure instead of 60 psi was used for this test so as not to exceed the rated capacity of the cell.

Second cell series

19. Static loads under the front, front tandem, and rear tandem wheels of the truck were measured with the wheels directly over cells 1 and 3 (3-in. depth) and cells 4 and 5 (9-in. depth) of the second series, first at 15-psi then at 60-psi tire pressure.

20. Sixteen dynamic stress tests were then run on the 3- and 9-in.-deep cells with a 15-psi tire pressure. A pass was made along the center line and at offsets of 3, 6, 9, 12, and 18 in., at vehicle speeds ranging between 1 and 4 mph.

21. Static load tests for 60-psi tire pressure only were repeated to determine if the traffic described in paragraph 20 had had any effect on the stresses. Only small differences in results were indicated as shown in the table in paragraph 29.

22. The final tests consisted of 15 dynamic loadings of both the 3- and 9-in.-deep cells along the center line and at offsets of 3, 6, 9, 12, and 18 in. with a tire pressure of 60 psi.

Soil Tests

23. Water content, density, CBR, cone index, and unconfined compression tests were conducted during construction and at various intervals during the traffic testing. Results of these tests are shown in table 1.

24. The depth of rutting throughout the entire test program was negligible, as can be seen on fig. 8.

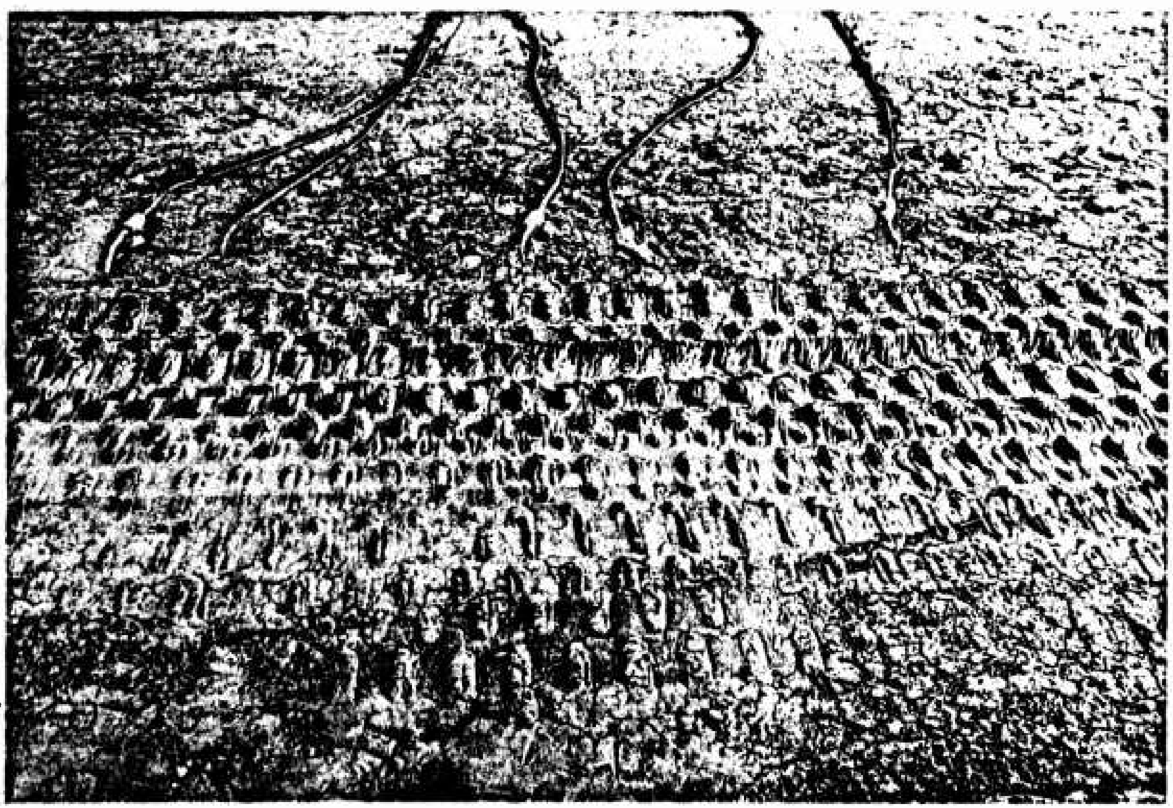

Fig. 8. Section after traffic

PART IV: ANALYSIS

25. The primary objective of the tests and of this analysis was to determine whether the WES earth pressure cell can be used to measure satisfactorily the vertical loads produced by a rolling pneumatic tire at various depths and offsets in a comparatively soft, wet, cohesive soil. The majority of the extensive WES experience in pressure distribution measurements has been with static loads and in firm soils. This experience showed the WES earth pressure cell to be a satisfactory instrument and one which yields results as good as those of any other pressure cells used to date. If this cell will also yield results under moving loads in soft soils that are comparable to results obtained in previous studies of static loads in firm soils, then use of the WES earth pressure cell for future work under the former conditions would be reasonable.

Consistency of Readings

26. One means of judging whether the pressure cells appear adequate to measure pressures induced in soft soils by moving loads is to examine the consistency of their readings under test conditions as nearly identical as it is possible to make them. It must first be realized that the measurement of soil pressures has been found very difficult, and that accuracies within about ±10 per cent for static loadings are usually considered quite good. The following table shows pressure cell readings that were made during the first pass of the test vehicle at slow speed (1-4 mph) directly over three cells at 6-in. depth, two cells at 3-in. depth, and two cells at 9-in. depth in the test section.

27. Examination of the table shows that the measurements are reasonable in magnitude and indicate a generally good pattern. Deviations greater than 10 per cent occur in only a few cases, and the largest deviation is only 14.3 per cent (for the front tandem at 60 psi). The pressure cells were recalibrated after the tests, and residual stresses examined in an effort to further improve the consistency, but without notable gain. It was further noted that the same cell (the first one)

Consistency of Readings

Wheels Directly over Cells

Cell No.	15-psi Tire Pressure: Front Wheel Stress psi	Front Wheel Dev from Avg psi	Front Wheel Dev from Avg %	Front Tandem Stress psi	Front Tandem Dev from Avg psi	Front Tandem Dev from Avg %	Rear Tandem Stress psi	Rear Tandem Dev from Avg psi	Rear Tandem Dev from Avg %	60-psi Tire Pressure: Front Wheel Stress psi	Front Wheel Dev from Avg psi	Front Wheel Dev from Avg %	Front Tandem Stress psi	Front Tandem Dev from Avg psi	Front Tandem Dev from Avg %	Rear Tandem Stress psi	Rear Tandem Dev from Avg psi	Rear Tandem Dev from Avg %
6-in. Depth, 1st Pass, Slow Speed																		
1	22.6	-3.2	12.4	19.5	-3.0	13.3	23.6	-1.2	4.8	27.5	-2.4	8.0	26.4	-4.4	14.3	30.7	-0.6	1.9
2	27.8	+2.0	7.8	23.5	+1.0	4.4	25.4	+0.6	2.4	30.0	+0.1	0.3	32.3	+1.5	4.9	33.6	+2.3	7.4
3	26.9	+1.1	4.3	24.4	+1.9	8.4	25.5	+0.7	2.8	32.3	+2.4	8.0	33.7	+2.9	9.4	29.7	-1.6	5.1
Avg	25.8			22.5			24.8			29.9			30.8			31.3		
3-in. Depth, 1st Pass, Slow Speed																		
1	25.0	-1.95	7.2	22.0	-2.0	8.3	24.0	-2.05	7.9	38.5	-3.75	8.9	34.0	-1.0	2.9	40.3	-1.85	4.4
3	28.9	+1.95	7.2	26.0	+2.0	8.3	28.1	+2.05	7.9	46.0	+3.75	8.9	36.0	+1.0	2.9	44.0	+1.85	4.4
Avg	26.95			24.0			26.05			42.25			35.0			42.15		
9-in. Depth, 1st Pass, Slow Speed																		
4	14.0	-1.15	7.6	12.2	-1.9	13.5	13.8	-1.2	8.0	18.5	-1.75	8.6	16.0	-1.95	10.9	17.3	-1.85	9.7
5	16.3	+1.15	7.6	16.0	+1.9	13.5	16.2	+1.2	8.0	22.0	+1.75	8.6	19.9	+1.95	10.9	21.0	+1.85	9.7
Avg	15.15			14.1			15.0			20.25			17.95			19.15		

read consistently lower than the other cell(s) under the same test conditions. It was concluded that the consistency of readings made with WES earth pressure cells under moving loads was of about the same order as that of the same cells under static loads as determined in previous WES studies and described in TM No. 3-323, Investigations of Pressures and Deflections for Flexible Pavements; Report No. 4, Homogeneous Sand Test Section, December 1954.

Effect of Close Proximity of Cells

28. The effect of close proximity of cells on cell readings was checked in the first series of tests. Cells 2, 4, and 5 were placed on 1-ft centers whereas cells 1 and 3 were spaced about 3 ft in front of and behind cell 2, respectively, on the center line. When loads were applied directly over the center line cells, no difference was noted in the readings of cells 1, 2, and 3 attributable to the propinquity of cells 4 and 5 to cell 2. It was concluded that spacings as small as 1 ft center to center have no adverse effect on registration. Based on these results, the cells for the second series of tests were spaced relatively close together to reduce the area required for the tests.

Comparison of Stresses under Static and Dynamic Loads

29. A comparison of stresses for the cases in which the static and dynamic loads were applied directly over the same cells is shown in the tabulation on the following page. This comparison shows stresses induced by the dynamic loads to be generally higher than those under static loads. Airfield studies show that moving loads produce lower stresses in pavements and subgrades than do stationary loads.* This appears to conflict with the data tabulated below; however, these moving aircraft

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* Accelerated Traffic Test at Stockton Airfield, Stockton, California (Stockton Test No. 2), Appendix D, Analysis of Pressure Readings. Prepared by O. J. Porter and Co., Consulting Engineers, Sacramento, California, May 1948.

Slow-moving Loads versus Static Loads
Wheels Directly over Cells

Tire Inflation Pressure psi	Cell No.	Cell Depth in.	Stress under Static Load, psi: Front Wheel	Front Tdm	Rear Tdm	Stress under Slow-moving, Dynamic Load, psi (Truck Speed of 1-4 mph): Front Wheel	Front Tdm	Rear Tdm	Difference (Dynamic Minus Static): Front Wheel psi	%	Front Tdm psi	%	Rear Tdm psi	%
15	94	0	28.0	26.0	27.0	30.0	28.0	28.0	2.0	7	2.0	8	1.0	4
	1	3	25.0	19.0	22.5	26.7	22.8	24.5	1.7	7	3.8	20	2.0	9
	3	3	29.0	25.0	27.2	28.5	25.6	26.2	-0.5	-2	0.6	2	-1.0	-4
		Avg 3	27.0	22.0	24.8	27.6	24.2	25.2	0.6	2	2.2	10	0.4	2
		6	23.3	----	----	24.1	20.7	23.4	0.8	3	---	--	---	--
	4	9	12.0	11.5	13.5	15.4	13.3	14.2	3.4	28	1.8	16	0.7	5
	5	9	15.0	13.5	14.8	16.1	15.3	15.8	1.1	7	1.8	13	1.0	7
		Avg 9	13.5	12.5	14.1	15.7	14.3	15.0	2.2	16	1.8	14	0.9	6
30	94	0	56.0	54.0	56.0	63.5	55.8	57.5	7.5	13	1.8	3	1.5	3
60	1	3	----	36.0	32.0									
	1	3	38.0*	36.0*	39.0*									
	Avg 1		38.0	36.0	35.5	39.9	33.1	40.5	1.9	5	-2.9	-8	5.0	14
	3	3	47.0	43.0	43.0									
	3	3	42.0*	38.0*	41.0*									
	Avg 3		44.5	40.5	42.0	47.0	38.0	45.5	2.5	6	-2.5	-6	3.5	8
		Avg 3	41.2	38.2	38.8	43.4	35.5	43.0	2.2	5	-2.7	-7	4.2	11
		6	----	----	----	26.6	25.7	28.5	---	--	---	--	---	--
	4	9	18.5	15.0	16.0									
	4	9	18.5*	15.0*	18.0*									
	Avg 4		18.5	15.0	17.0	21.1	16.7	18.7	2.6	14	1.7	11	1.7	10
	5	9	18.5	18.5	19.0									
	5	9	18.0*	16.5*	17.0*									
	Avg 5		18.2	17.5	18.0	22.5	20.2	21.8	4.3	24	2.7	15	3.8	21
		Avg 9	18.4	16.2	17.5	21.8	18.4	20.2	3.4	18	2.2	14	2.7	15

Note: All stresses under static loads are single readings except 3 readings were made for front wheel at 15 psi over 6-in. cell; all stresses under moving loads are averages of several readings.
Static data without asterisk were measured before traffic. Static data with asterisk (*) were measured after several passes.

loads were somewhat faster than the slowly moving loads in this study. Also, the moving wheels in this study were driving wheels which may have some effect. Relation between cell position and surface roughness also might affect measured stresses. A re-examination of some unpublished airfield data that include a few measurements under moving loads at speeds comparable to those used in this study indicates that the higher dynamic results found in this study are probably valid.

Comparison of the Effects of Tire Pressure on Stresses

30. The following table shows that the stress induced by the tire at the higher inflation pressure (50 psi for surface measurements, 60 psi for measurements at other depths) was consistently higher at the same depth than that induced by the tire at the lower pressure (15 psi). This is to be expected and indicates that the pressure cells were at least giving qualitatively correct readings. The average stress for the three tires at the higher inflation pressure was 30.2 psi greater than that for the lower pressure at the surface and 4-5 psi greater at 6- and 9-in. depths.

31. The stress under the 15-psi tire was approximately twice the inflation pressure at the surface, and about equal to the inflation pressure at the 9-in. depth. The higher tire pressure produced stresses only about 15 per cent higher than the inflation pressure at the surface (58.9-psi stress vs 50-psi inflation), and at the 9-in. depth the measured stress was only one-third of the inflation pressure.

Effect of Tire Pressure, Wheels Directly over Cells

(Truck speed approximately 1 to 4 mph)

Depth of Cell in.	Stress in psi under 15-psi Tire Pressures: Front Wheel	Front Tdm	Rear Tdm	Avg	Stress in psi under 50- and 60-psi Tire Pressures: Front Wheel	Front Tdm	Rear Tdm	Avg	Diff in Avg Stress under High and Low Tire Pressures, psi
0	30.0	28.0	28.0	28.7	63.5*	55.8*	57.5*	58.9*	30.2*
3	27.6	24.2	25.2	25.7	43.4	35.5	43.0	40.6	14.9
6	24.1	20.7	23.4	22.7	26.6	25.7	28.5	26.9	4.2
9	15.7	14.3	15.0	15.0	21.8	18.4	20.2	20.1	5.1

Note: Compare stresses at 0-in. depth with values of average contact pressure quoted in paragraph 11.
* 50 psi.

Effect of Passes at 15- and 60-psi Tire Pressures

32. Changes in the maximum stress for a given cell occurred from

pass to pass as shown on plate 6, but no definite trend was apparent. It should be noted that the cells at the 3- and 9-in. depth, which were in the same test section, show somewhat similar patterns. No explanation has been found for the general increase in stress following the second pass and decrease following the seventh pass.

Stress Distribution Patterns

33. Plate 7 shows the pattern of average stresses (for 3 wheels) in the direction of tire travel and perpendicular to tire travel. Values are plotted at offsets of 0, 3, 6, 9, and 12 in. for 0-, 3-, 6-, and 9-in. depths. The solid lines represent the average stresses in the direction of tire travel, and the dashed lines represent those perpendicular to tire travel. The plotted points on the dashed lines are averages of all stresses measured at given offsets and include stresses measured both right and left of the line of tire travel; thus the dashed lines are symmetrical. The plotted points on the solid lines are the average stresses at given distances from the center of the cells used. The asymmetry of the solid lines of the plots of 0- and 3-in. depths suggests that the maximum stress may not have occurred at the center of the cell. However, careful examination of the records showed that the maximum stress occurred directly over the center of the cell, in the majority of cases on record, and further that stresses measured by the cell when the wheel had passed it were nearly always higher than stresses measured when the wheel had not yet reached the cell (for the same distances). The few records which indicate occurrence of maximum stress off center are believed to have been the result of malfunctioning equipment or movement of cells. This phenomenon will be studied more carefully in future tests of this kind. Results of an examination of records of stresses at 15-psi inflation pressure on cells at 3- and 9-in. depths to determine the position of maximum stress relative to the center of the cells are shown in the following table.

Wheel	Total No. of Readings	No. Readings Maximum Stress at Cell	No. Readings Maximum Stress Ahead of Cell	Range and Average Distance Ahead, in.	No. Readings Maximum Stress Behind Cell	Range and Average Distance Behind, in.
			3-in. Depth			
Front	11	2	1	(1.0) 1.0	8	(0.4-2.6) 1.5
Front tandem	8	4	0	--	4	(1.0-1.5) 1.2
Rear tandem	14	12	1	(0.7) 0.7	1	(0.4) 0.4
Total	33	18	2	(0.7-1.0) 0.8	13	(0.4-2.6) 1.3
			9-in. Depth			
Front	9	2	2	(0.9-1.1) 1.0	5	(0.7-1.5) 1.1
Front tandem	13	10	3	(0.8-1.1) 0.9	0	--
Rear tandem	13	8	5	(0.6-1.9) 1.1	0	--
Total	35	20	10	(0.6-1.9) 1.0	5	(0.7-1.5) 1.1

Effect of Speed

34. The truck speed was measured on each pass, but because of difficulty in exactly controlling speeds at low ranges, the speeds varied during the course of the testing from about 1 to 4 mph. An attempt was made to show a relationship between speed at which the pass was made and the stresses shown plotted on plate 5 by superimposing the proper speed plots. However, no relationships were found, and therefore the speed data are not shown.

Comparison of Measured and Computed Stresses

35. Computations were made of the theoretical stresses at 0-, 3-, 6-, and 9-in. depths directly under the center of each of the three truck wheels for 15- and 60-psi tire pressures. The loads were 2800 lb each for the front and front tandem wheels and 3100 lb for the rear tandem wheel. These loads are approximate since suitable scales for accurate weighing of individual wheels were not available. The contact area was measured by inking the treads of the tire and gently lowering it to a sheet of paper placed on a thin steel plate lying on smooth level ground. The area was that enclosed by a line drawn around the extremities of the roughly elliptical pattern of inked impressions. The loads, areas, and average contact pressures (loads divided by areas) are shown in the following table.

Wheel	Load lb	15-psi Tire Pressure Area sq in.	15-psi Tire Pressure Avg Contact Pressure, psi	60-psi Tire Pressure Area sq in.	60-psi Tire Pressure Avg Contact Pressure, psi
Front	2800	93.08	30.08	53.28	52.55
Front tandem	2800	96.10	29.14	54.94	50.96
Rear tandem	3100	101.97	30.40	55.58	55.78

It was assumed that the various elliptical areas were circular and the radii of these respective circles were computed. Theoretical stresses directly under the center of the loads were computed from the formula for vertical stress on horizontal planes for uniform circular loads,*

$$\frac{\sigma_z}{p} = 1 - \frac{z^3}{\left(z^2 + r^2\right)^{3/2}}$$

where

σ_z is the theoretical stress in psi

p is the average contact pressure in psi (see preceding table)

z is depth in in.

r is radius of equivalent circle.

36. A comparison of the measured stresses and the computed theoretical stresses is shown in the following table.

Depth in.	Wheel	15-psi Meas'd Stress psi	15-psi Comp'd Stress psi	15-psi $\frac{\text{Meas'd}}{\text{Comp'd}} \times 100$	60-psi Meas'd Stress psi	60-psi Comp'd Stress psi	60-psi $\frac{\text{Meas'd}}{\text{Comp'd}} \times 100$
0	Front	30.0	30.1	100	----	52.6	
	Front tdm	28.0	29.1	96	----	51.0	
	Rear tdm	28.0	30.4	92	----	55.8	
3	Front	27.6	26.7	103	43.4	41.8	104
	Front tdm	24.2	26.0	93	35.5	40.9	87
	Rear tdm	25.2	27.3	92	43.0	44.9	96
6	Front	24.1	17.9	135	26.6	23.2	115
	Front tdm	20.7	17.6	118	25.7	23.0	112
	Rear tdm	23.4	18.8	124	28.5	25.3	113
9	Front	15.7	11.3	139	21.8	13.3	164
	Front tdm	14.3	11.2	128	18.4	13.2	139
	Rear tdm	15.0	12.1	124	20.2	14.5	139

* WES TM No. 3-323, Investigations of Pressures and Deflections For Flexible Pavements, Report No. 1, Homogeneous Clayey Silt Test Section, March 1951.

It will be noted that measured stresses vary from 87 to 164 per cent of computed stresses and that the agreement is considerably better at 0- and 3-in. depths than at 6- and 9-in. depths. Further, there is a tendency for measured readings near the surface to be somewhat less than computed readings while at 6- and 9-in. depths the measured values vary from 12 to 64 per cent higher than computed values.

PART V: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

37. The principal conclusion resulting from this pilot test study is that stress measurements under driven truck tires made with the WES earth pressure cell in a fairly soft soil appear to be of the same order of accuracy as stress measurements that have been made under static loads in firmer soils. The WES earth pressure cell will be used, therefore, to record stresses under pneumatic tires in future vehicle mobility research, at least until such time as a more accurate device becomes available.

38. Examination of the data obtained from the study leads to the following observations:

a. The consistency of readings made with the WES earth pressure cells under the moving loads was comparable to the consistency of readings under static loads in previous WES studies.

b. The spacing of cells as close as 1 ft to each other appeared to have no adverse effects on their registration.

c. A comparison of stresses produced under slow-moving loads and static loads in this study showed the former to be usually greater.

d. The stress induced by a tire at a higher inflation pressure (50 and 60 psi) was consistently greater than that of a tire at a lower inflation pressure (15 psi). At the surface the 50-psi tire produced a stress 30.2 psi higher than the one produced by the 15-psi tire. At 6- to 9-in. depths the difference was 4 to 5 psi.

e. Change in stress occurred from pass to pass, even though rutting was not significant, but the trend was not definite.

f. The various stress distribution patterns drawn were typical.

g. No effect of speed on induced stresses was noted for the small range of speeds used (1 to 4 mph).

Recommendations

39. Based on the results of this study, it is recommended that the following tests be performed using the WES earth pressure cell.

a. Additional and similar tests on a larger test section with a CBR of less than 5 per cent.

b. Measurements of stresses with a larger number of pressure cells placed at different depths, offsets, and angles.

c. Measurement of stresses with the same vehicle at various loads and speeds.

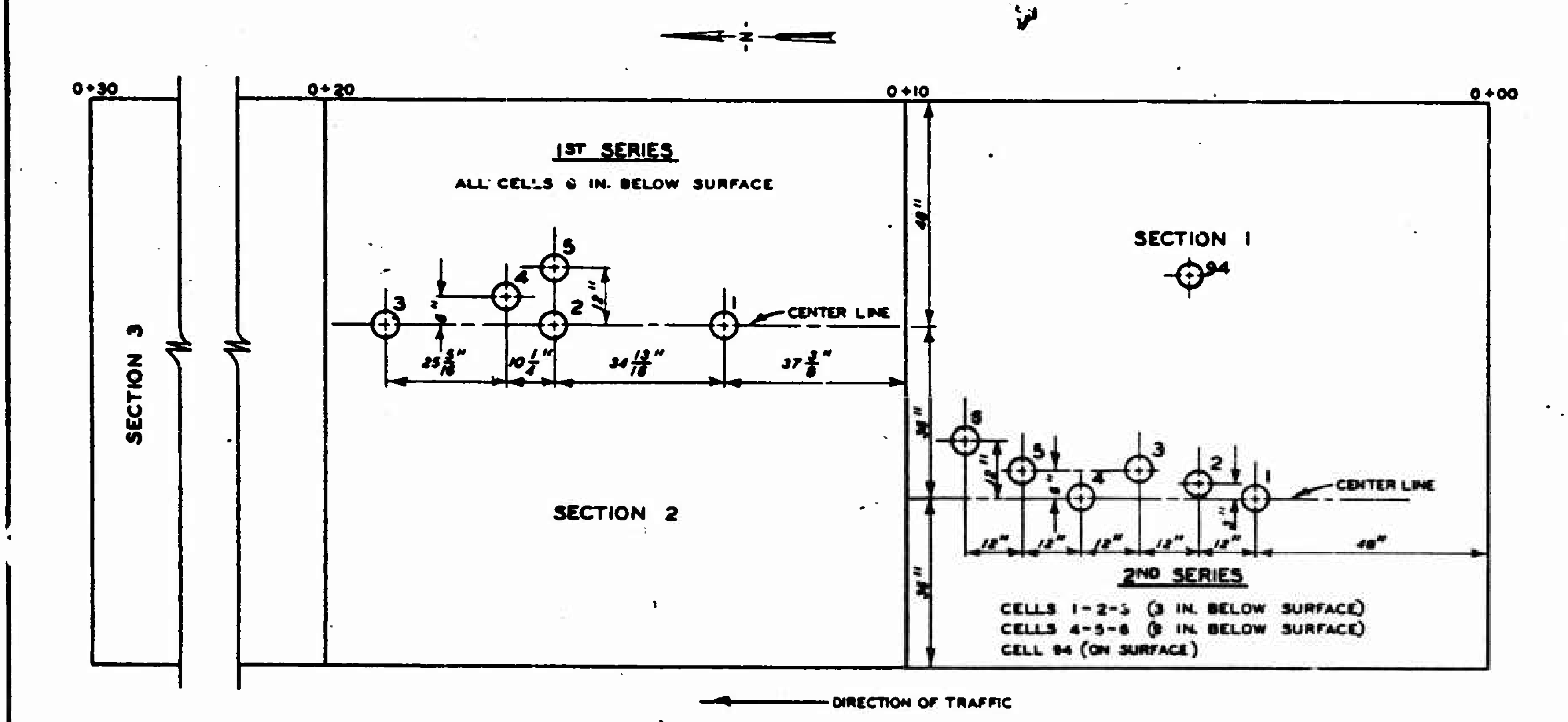
d. Measurement of stresses under other types of vehicles, including tracked vehicles.

40. It is also recommended that other pressure cell types be tested when they are available.

Table 1

Soil Test Data

0 Pass								10 Passes							
Location	Depth in.	Water Content %	Density lb/cu ft	CBR %	Cone Index in Pit	Cone Index at Random	Unconfined Comp. Strength tons/sq ft	Location	Depth in.	Water Content %	Density lb/cu ft	CBR %	Cone Index in Pit	Cone Index at Random	Unconfined Comp. Strength tons/sq ft
Section 1	0					181	2.08	Section 1	0					238	
	3	22.1	98.4	4	186	207			3	25.6	97.4	5	160	306	
	6					228			6					289	
	9	23.1	97.9	6	---	215			9	23.5	97.7	6	165	310	
	12					211			12					313	
	15	24.2	96.0	5	150				15	23.8	96.5	5	155	---	
	18					248			18					320	
	24	20.9	86.8	4	158				24	21.2	89.8	4	162	---	
Section 2	0					103	1.87	Section 2	0					119	1.65
	3					295			3					250	
	6					277			6					237	
	9					244			9					248	
	12					265			12					230	
	15								15						
	18					228			18					206	
	24					280			24					228	
Section 3	0	26.1	95.8	4	146	102		Section 3	0	25.3	97.6	4	163		
	3					200			3						
	6	23.9	98.5	7	214	270			6	26.5	95.3	5	168		
	9					285			9						
	12	23.4	90.4	5	212	297			12	24.7	96.0	6	156		
	15					275			15						
	18					300			18						
	24					302			24						

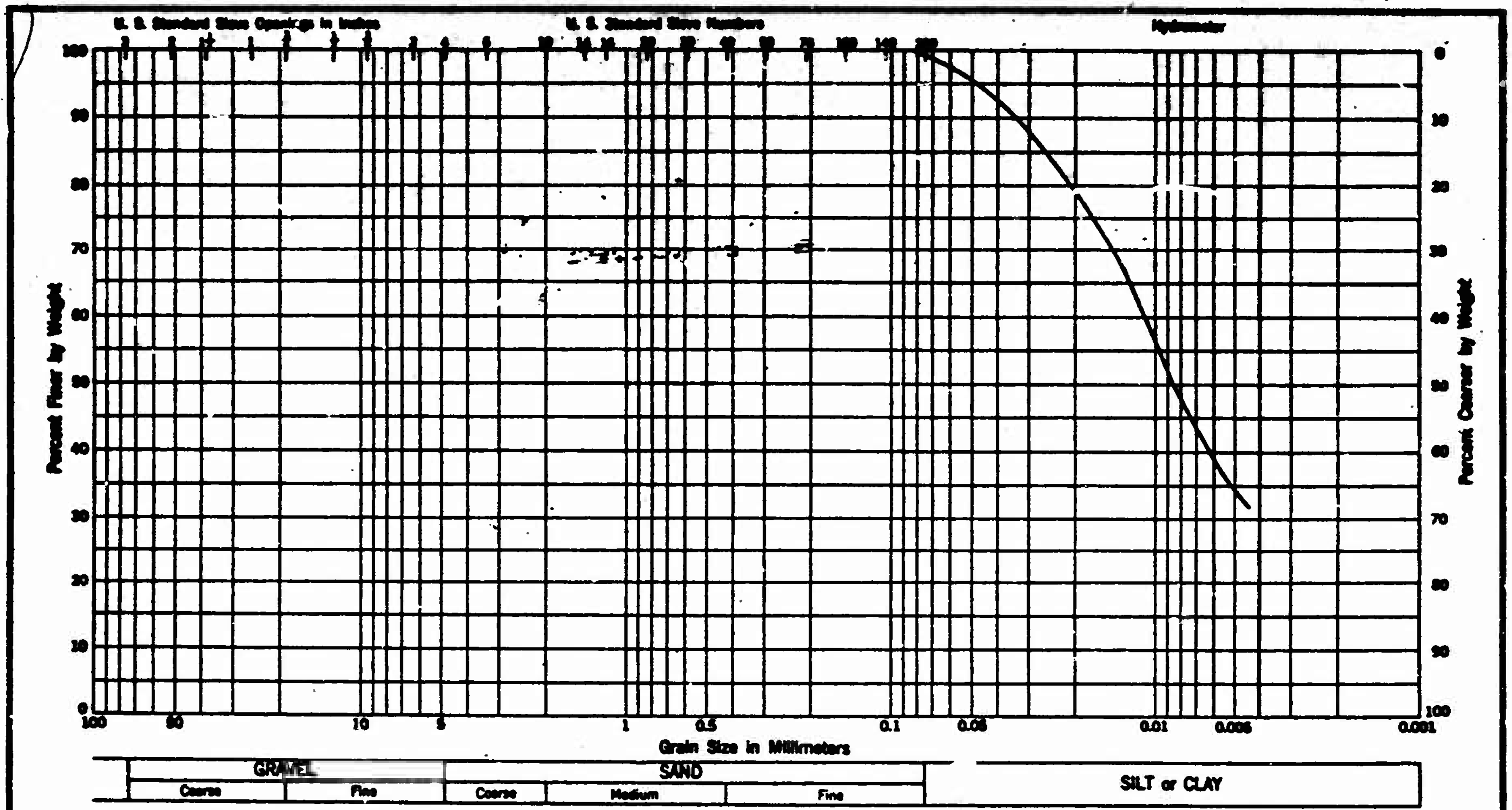


LAYOUT OF TEST AREA
VEHICLE MOBILITY
STRESS DISTRIBUTION

021656-B

PLATE 1

28862



Number	Depth	Natural Moisture	L.L.	P.L.	P.I.	Classification
			60	21	39	BUCKSHOT CLAY CH
101253-B						

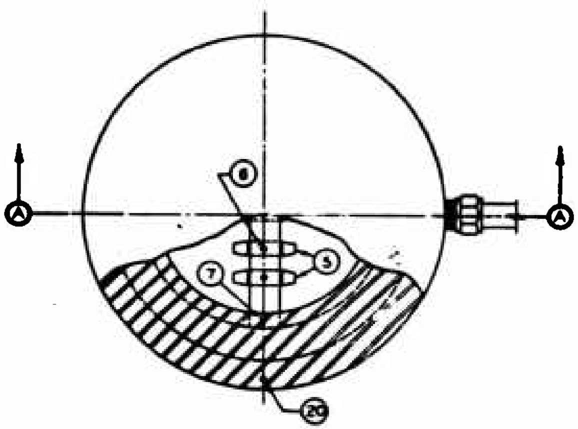
SOIL
CLASSIFICATION DATA

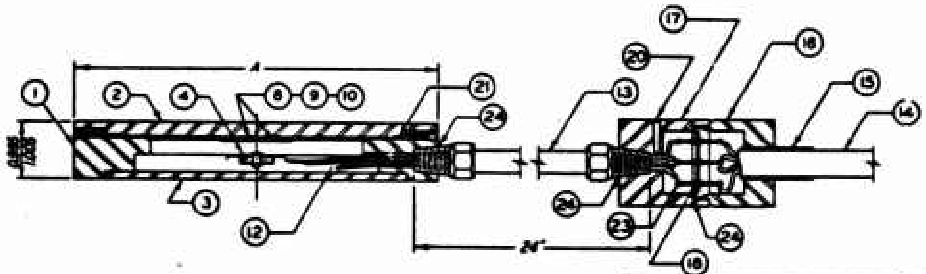
PLATE 2

SCHEDULE OF DIMENSIONS - INCHES									
DIMENSION		A	B	C	D	E	F	G	H
DRAWING NO.		B 173e C 174e C 175e	C 174e	C 174e C 176e	C 175e	C 175e	C 175e	C 175e	C 174e
CELL	CAPACITY								
SIZE 6	25	5.995 6.005	0.037 0.038	0.120 0.130	0.020 0.021	5.745 5.755	4.495 4.505	4.995 5.005	5.820 5.830
	50	do.	0.054 0.055	0.120 0.130	0.025 0.026	do.	do.	do.	do.
	100	do.	0.074 0.075	0.183 0.193	0.032 0.033	do.	do.	do.	do.
	200	do.	0.100 0.101	0.183 0.193	0.032 0.033	do.	do.	do.	do.
SIZE 12	25	11.995 12.005	0.037 0.038	0.120 0.130	0.020 0.021	11.745 11.755	10.495 10.505	10.995 11.005	11.820 11.830
	50	do.	0.054 0.055	0.120 0.130	0.025 0.026	do.	do.	do.	do.
	100	do.	0.074 0.075	0.183 0.193	0.032 0.033	do.	do.	do.	do.
	200	do.	0.100 0.101	0.183 0.193	0.032 0.033	do.	do.	do.	do.

BILL OF MATERIAL

ITEM NO.	QUAN.	DWG. NO.	DESCRIPTION	REMARKS
1	1	C 174e	Diaphragm	Type 416 - Stainless Steel
2	1	C 175e	Face Plate	do.
3	1	C 176e	Cover Plate	do.
4	1	C 177	Terminal Strip	Thermosetting Material Type C-CR Synthane or equal
5	5	C 177	Terminal Lugs	Brass
6	5	C 177	Terminal Rivets	do.
7	2	C 177	Terminal Screws	do.
8	4	C 179e	SR-4 Bakelite Gages, 120	Ruge deForest or equal
9	-	-	Bakelite Cement	do.
10	-	-	Moisture Resistant Wax	Sun Oil Co. no. 1290 or equal
11	-	-	Gage Lead Wires	No. 28 Solid Conductor
12	4	-	No. 20 Lacquered Glass Braid Radio Hook-up Wire	Deltabeston SI 57388 or Equal, G.E. Company
13	1	-	Flexible Tubing 1/8" - 24"	Stain. Steel Ribbon Braid 1/8" Male Pipe Fittings Titeflex no. 4101 or equal
14	1	-	4-wire Cable	Not to be Furnished in this Contract
15	1	-	Annealed Copper Tubing 3/8" O.D.	do.
16	1	C 177	Hermetic Seal Housing	Male - Stainless Steel
17	1	C 178	do.	Female - Stainless Steel
18	1	-	Kovar Seal	Stupakoff Type FK-4 Code no. 954004
19	1	C 179e	Advance Wire	Driver - Harris Co. or equal
20	3	-	Standard Taper Pins - 3/0	Stainless Steel
21	-	-	Mercury - "CP" Grade	
22	-	-	Welding Rod	...ss Steel - 12-14 % Cr
23	-	-	50-50 Rosin Core Solder	To be used in Gage Chamber
24	-	-	65-35 Solid Solder	To be used in Solder Sealing





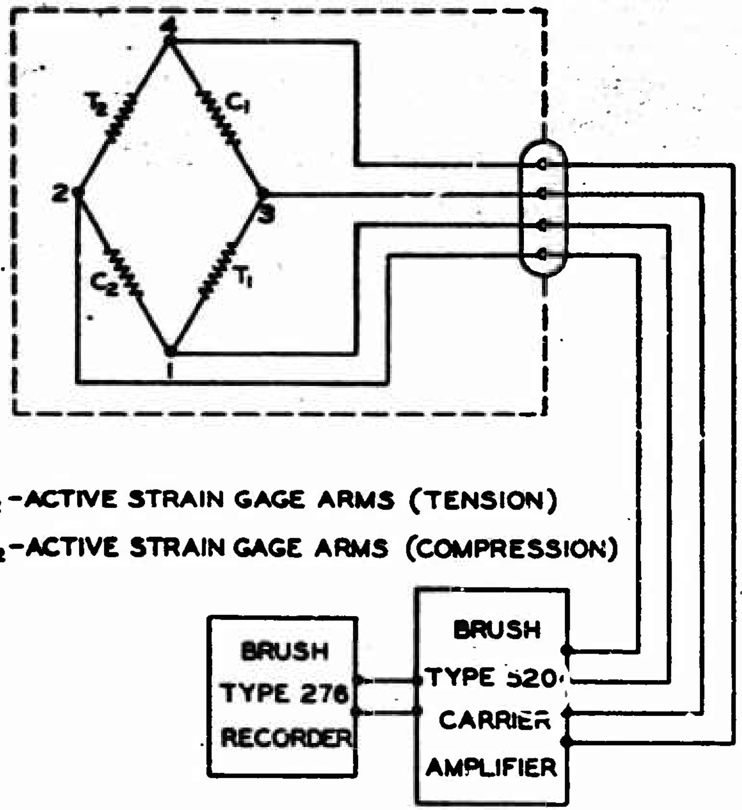
SECTION A-A

LETTER	REVISIONS	BY	DATE	APPROVAL	DATE
	WAS OMITTED			Director	
	WAS 051 - 052 WAS 036 - 025 WAS .030 - 031 WAS 035 - 036			Chief, S...	
	INCLUDED 10 PSI CAPACITY WAS 041 - 042 WAS 039 - 300			Checked by	
	WAS SELDEN 9938 DID NOT SPECIFY "HELIARC" PROCESS			Drawn by	

W. E. S. EARTH PRESSURE CELL

ASSEMBLY

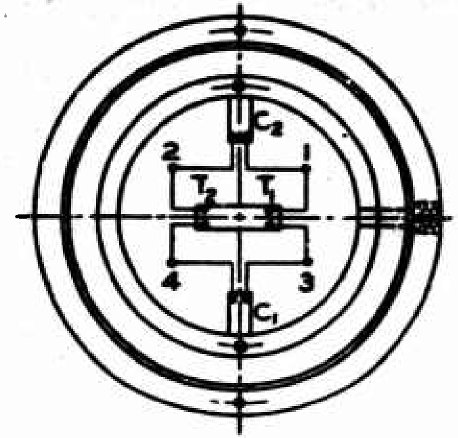
PLATE 3



T_1, T_2 – ACTIVE STRAIN GAGE ARMS (TENSION)

C_1, C_2 – ACTIVE STRAIN GAGE ARMS (COMPRESSION)

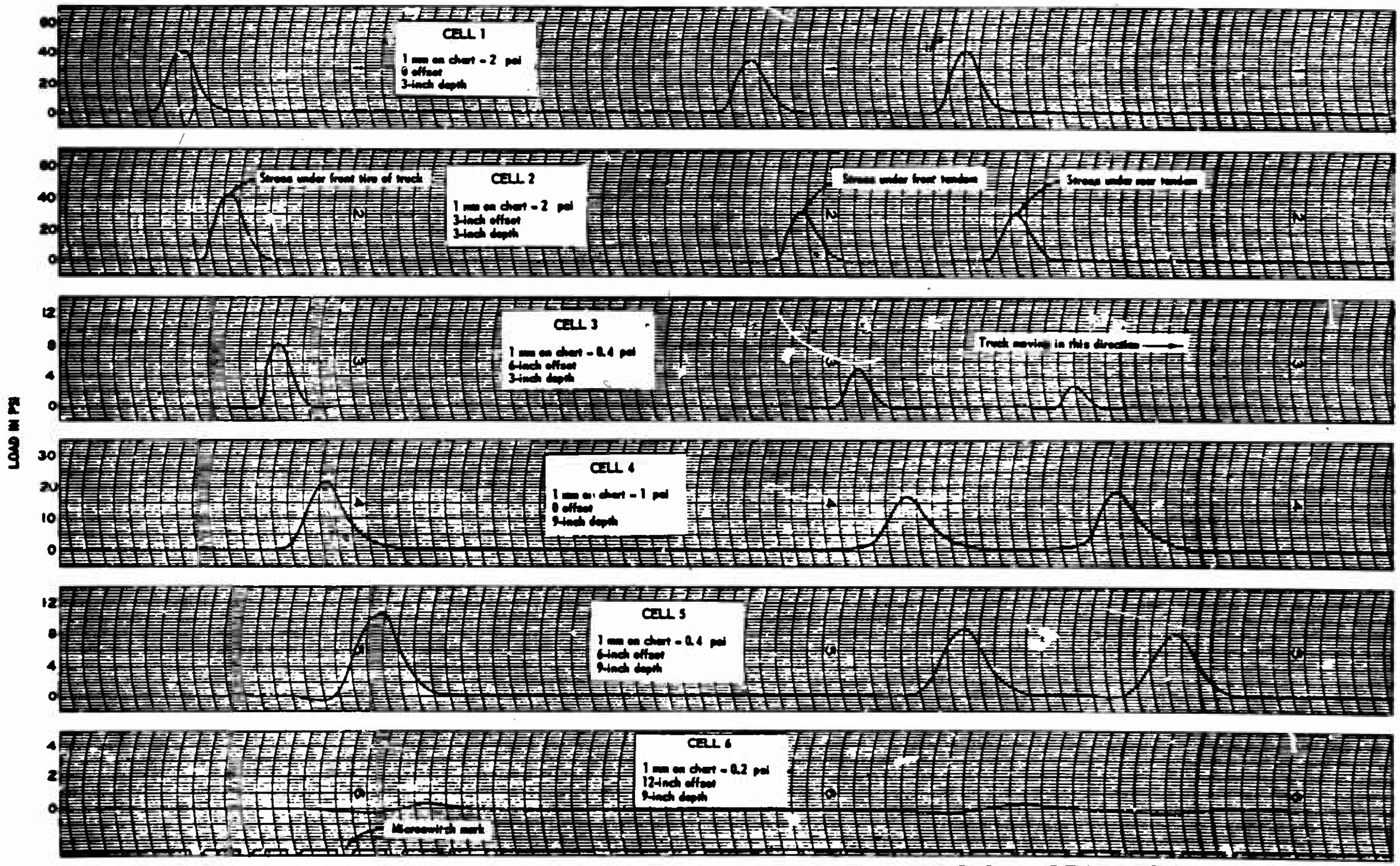
ELECTRICAL SCHEMATIC DIAGRAM



LOCATIONS OF GAGES ON DIAPHRAGM

DETAILS OF
WES EARTH PRESSURE CELL

PLATE 4

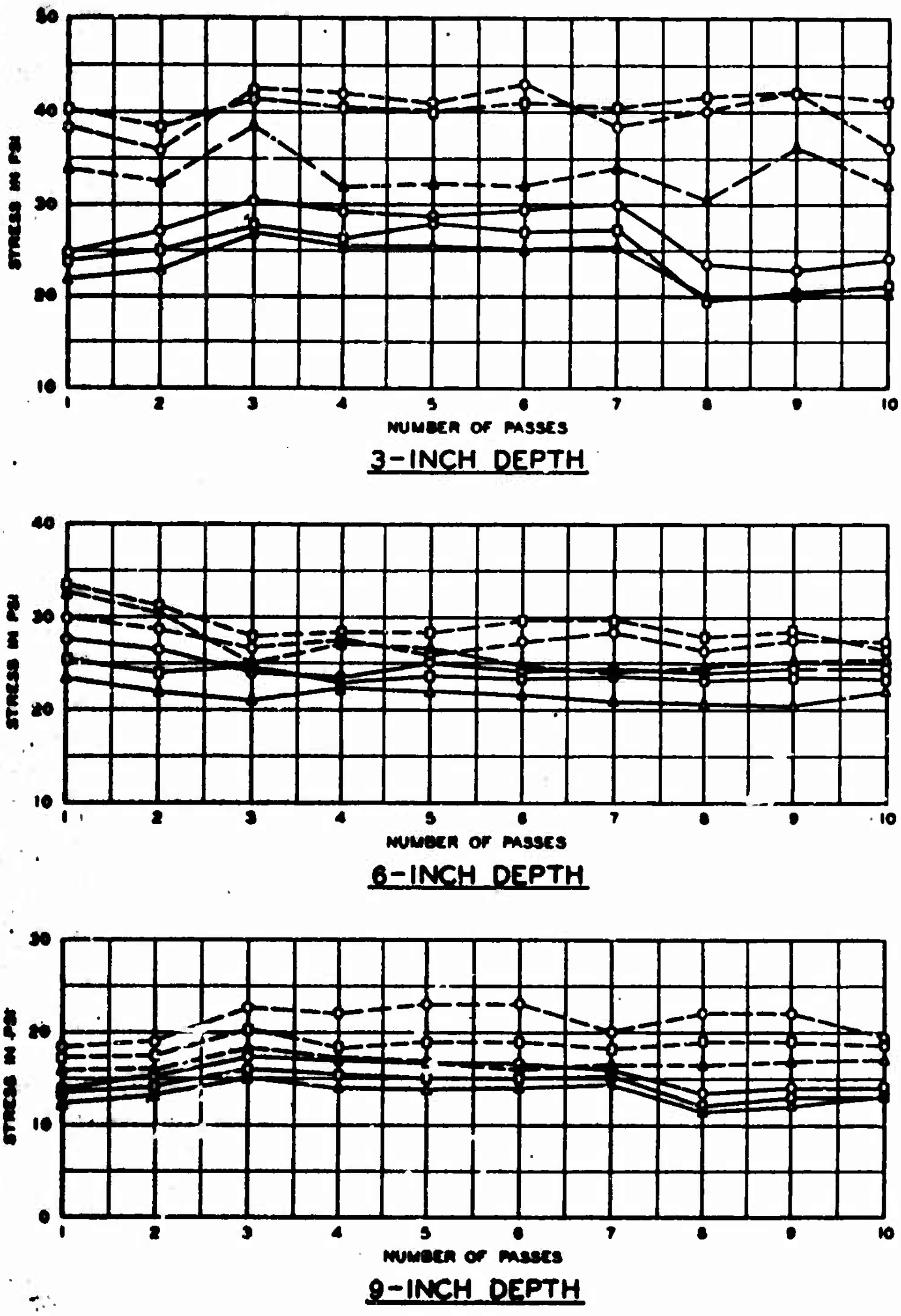


NOTE: Truck traveled directly over Cells 1 and 4.

040456 A

TYPICAL RECORDED STRESS CHART
3- AND 9-INCH DEPTH
60-PSI TIRE PRESSURE

PLATE 5



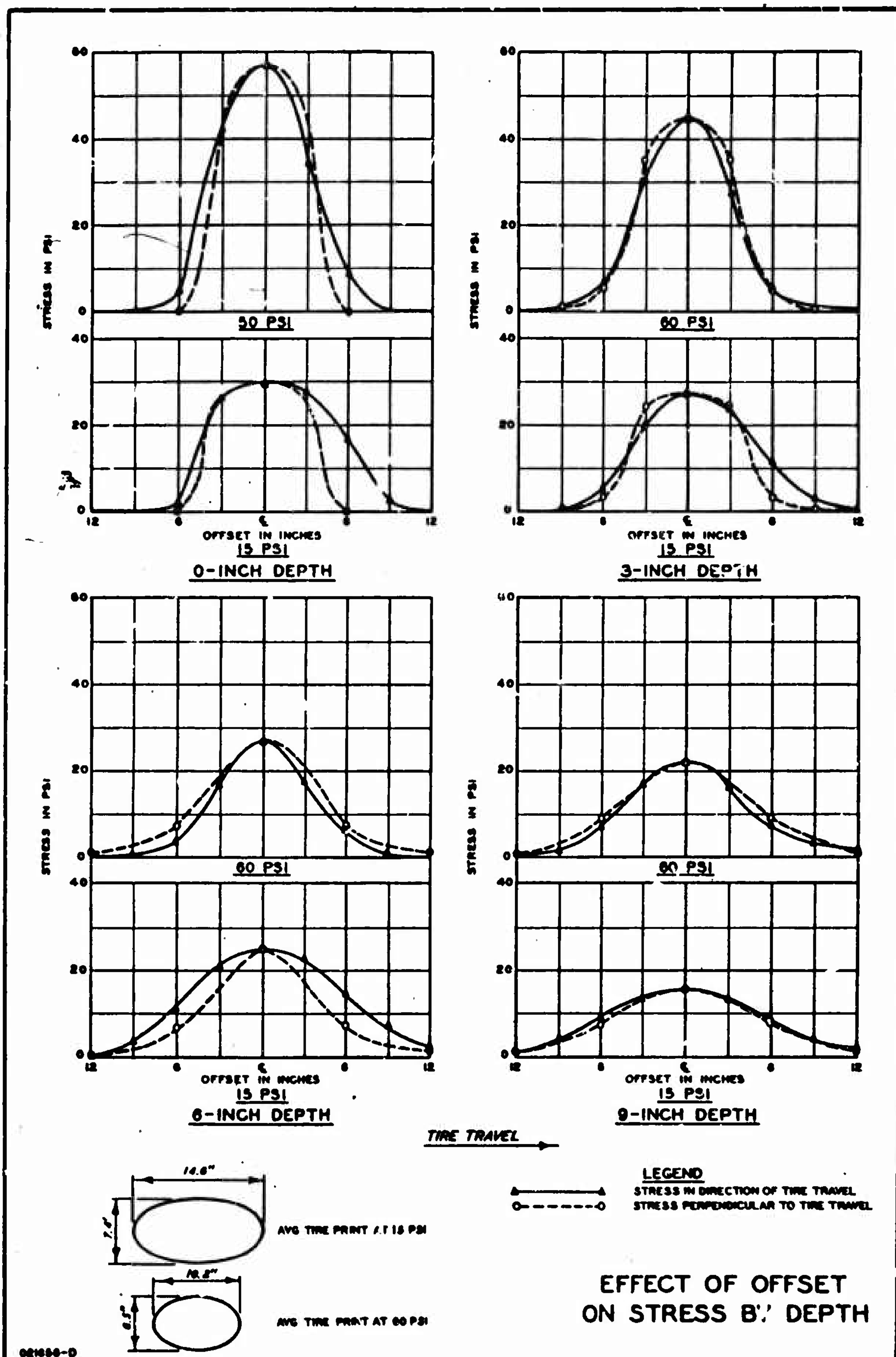
LEGEND

- O STRESS UNDER FRONT WHEEL
- △ STRESS UNDER FRONT TANDEM
- □ STRESS UNDER REAR TANDEM
- ——— 15-PSI TIRE PRESSURE
- — — 60-PSI TIRE PRESSURE

EFFECT OF PASSES ON STRESS BY DEPTH

ZERO OFFSET

021050-C



EFFECT OF OFFSET ON STRESS BY DEPTH